P 511-517=7 PD 00-12-2001

E-

Latching Micromagnetic Relays

Meichun Ruan, Jun Shen, *Senior Member, IEEE*, and Charles B. Wheeler, *Member, IEEE*

***Abstract*—This paper describes the underlying principles, design and operation of a new type of latching micromagnetic relay. The device is based on preferential magnetization of a soft magnetic cantilever in a permanent external magnetic field. Switching between two stable states is accomplished by momentarily changing the direction of the cantilever's magnetization by passing a short current pulse through a planar coil situated under the cantilever. Once the relay is switched, it is held in this nonvolatile state by the permanent external magnetic field. Latching operation has been demonstrated for devices having two different cantilever geometries and a variety of sizes. Characterization has been performed under dc and ac conditions. The minimum (lead-to-lead) resistance through the switch is approximately 50 mΩ. The switching current and minimum switching pulse width are 79 mA and 0.2 ms, respectively. The operating voltage is about 5 V. The switching energy consumption is $< 93\ \mu$J. [553]**

I. Introduction

Latching relays are a bistable type of electromagnetic switch that can retain an "on" or "off" state in the absence of applied power and consequently, are nonvolatile. Some additional component, such as a magnet that can reversibly bind or oppose the normal switch operation, is normally added to a relay to achieve the latching feature. This type of switch is particularly useful for applications that require minimal power consumption, such as satellites and portable electronics, and also for low resistance, programmable configuration switches, perhaps in automatic test equipment (ATE) and automobile electronics.

The current interest in and development of microelectromechanical (MEMS) switches has highlighted the prospect of using microelectronics fabrication methods to produce microlatching relays. The motivation being that batch-fabrication will inevidably reduce production costs while enabling new applications that arise from the reduction in size and the ability to integrate multiple components. Recent publications have described a number of high-quality microswitches based on electrostatic [1]–[7], magnetic [8]–[18], and thermal actuation [19]–[21], but of the reports we are aware of, only the thermal switches reported by Sun *et al.* [19] and Kruglick *et al.* [20] have demonstrated latching operation. Presumably, this is attributable to the difficulty of devising a latching mechanism compatible with surface micromachining fabrication methods that are typically used to fabricate electrostatic and magnetic switches.

Manuscript received March 23, 2000; revised September 4, 2000. The work of J. Shen and C. B. Wheeler was supported in part from the Air Force Research Laboratory/VS, Kirtland AFB, NM 87117-5776 USA. Subject Editor D.-I. Cho.

M. Ruan and C. B. Wheeler are with Microlab, Inc., 341 E. Alamo Dr., Chandler, AZ 85225 USA.

J. Shen is with the Department of Electrical Engineering and Center for Solid State Electronics Research, Arizona State University, Tempe, AZ 85286 USA (e-mail: jshen@asu.edu).

Publisher Item Identifier S 1057-7157(01)05035-1.

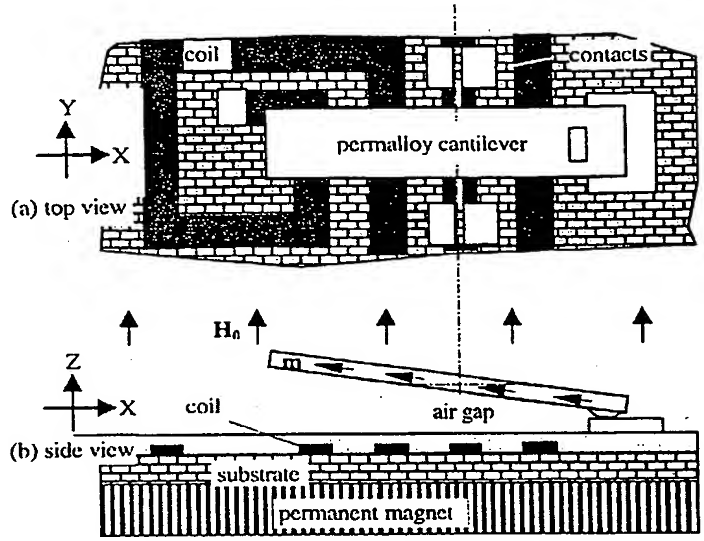

Fig. 1. Top and side views of the latching relay. Planar coils are integrated on the same substrate underneath the cantilever. A permanent magnet provides the constant magnetic field H_0. The X-component of the coil current-induced magnetic field changes the magnetization of the permalloy beam (m), which results in a torque on the beam to force it either down or up. The permanent magnetic field holds the state of the beam (either up or down) so that no power is necessary during the quiescent state (latching).

In this paper, we describe a new type of latching (bistable) micromagnetic relay based on the preferential magnetization of a permalloy cantilever in a static external magnetic field. Switching between two stable states is accomplished by momentarily energizing a planar coil that is situated under the cantilever. The switching coil produces magnetic field that reverses the magnetization of the cantilever and causes the relay to switch. Once switched, the device is latched by the external field and will remain in this state until the coil is reenergized. In the following sections, we will explain the operation principles and discuss the design, fabrication, and device performance.

II. Principle of Operation

The basic structure of the microswitch is illustrated in Fig. 1. The device consists of a cantilever, an embedded planar coil, a permanent magnet, and the necessary electrical contacts. The cantilever is a two-layer composite consisting of a soft magnetic material (e.g., NiFe permalloy) on its topside and a highly conductive material, such as Au, forms the bottom surface. The cantilever is supported by torsion flexures from the two sides [see Figs. 1 and 2(a)]. The flexures are electrically conductive and form part of the conduction path when the switch is closed. A second design variation that has also been explored is a more conventional structure where the cantilever is fixed at one end and is free to deflect at the opposite end [see Fig. 2(b)]. The

1057–7157/01$10.00 ©2001 IEEE

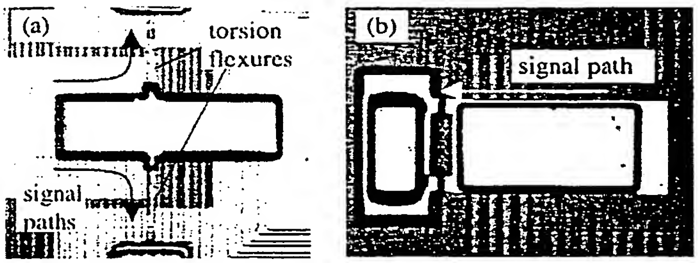

Fig. 2. Photographs of the fabricated devices. (a) Hinged type: the cantilever dimensions are 800 μm × 200 μm × 25 μm with torsion flexures located in the cantilever center. Each flexure has dimensions of 280 μm × 20 μm × 3 μm. The air gap spacing is 12 μm. The number of coil turns is 20. (b) One-end-fixed type: the cantilever size is 700 μm × 300 μm × 5 μm with an additional 25-μm-thick permalloy layer in the main body of the cantilever (the rectangular shaped region). The air gap spacing is 12 μm. The number of coil turns is 20.

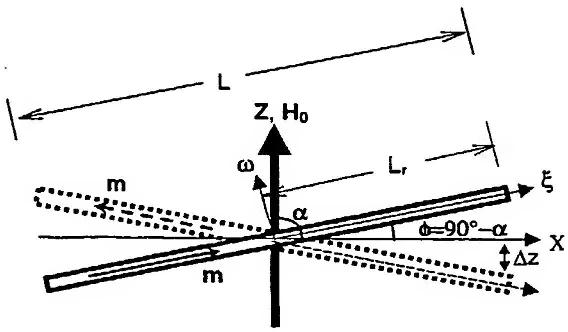

Fig. 3. Schematic drawings of the hinged type relay for discussions. H_0 is the magnetic field due to the permanent magnet, ξ is the long axis of the beam (ω is perpendicular to ξ and intersects with ξ at the rotation axis of the beam), m is the magnetic moment of the beam, α is the angle between H_0 and ξ, $\phi = 90° - \alpha$, and Δz is the deflection height at the contact end from the horizontal position. The air gap spacing is equal to Δz when it reaches maximum (the switch closes).

contact end to the right of the cantilever can be deflected up or down by applying a current through the coil. When it is in the "down" position, the cantilever makes electrical contact with the bottom conductor, and the switch is "on" ("closed"); when the contact end is "up", the switch is "off" ("opened"). The permanent magnet holds the cantilever in either the "up" or the "down" position after switching, making the device a latching relay.

A. Method to Produce Bistability

When the length L of a permalloy cantilever is much larger than its thickness t and width w, the direction along its long axis (L) becomes the preferred direction for magnetization (easy axis). When such a cantilever is placed in a uniform permanent magnetic field, a torque is exerted on the beam (see Fig. 3). The torque can be either clockwise or counterclockwise, depending on the initial orientation of the beam with respect to the magnetic field. When the angle (α) between the beam axis (ξ) and the external field ($\boldsymbol{H}_0$) is smaller than 90°, the torque is counterclockwise; and when α is larger than 90°, the torque is clockwise. The bidirectional torque arises because of the bidirectional magnetization (by $\boldsymbol{H}_0$) of the beam (from left to right when $\alpha < 90°$, and from right to left when $\alpha > 90°$). Due to the torque, the beam tends to align with the external magnetic field ($\boldsymbol{H}_0$). However, when a mechanical force (such as the elastic torque of the beam, a physical stopper, etc.) preempts to the total realignment with $\boldsymbol{H}_0$, two stable positions ("up" and "down") are available, which forms the basis of latching in the relay.

B. Electrical Switching

If the bidirectional magnetization along the easy axis of the beam arising from $\boldsymbol{H}_0$ can be momentarily reversed by applying a second magnetic field to overcome the influence of ($\boldsymbol{H}_0$), then it is possible to achieve a switchable latching relay. This scenario is realized by situating a planar coil under the cantilever to produce the required temporary switching field. The planar coil geometry was chosen because it is relatively simple to fabricate, though other structures (such as a wrap-around type) are also possible. The magnetic field ($\boldsymbol{H}_{\text{coil}}$) lines generated by a short current pulse loop around the coil. It is mainly the ξ-component (along the beam, see Fig. 3) of this field that is used to reorient the magnetization in the beam. The direction of the coil current determines whether a positive or a negative ξ-field component is generated. After switching, the permanent magnetic field holds the beam in this state until the next switching event is encountered. Since the ξ-component of the coil-generated field ($\text{H}_{\text{coil-}\xi}$) only needs to be momentarily larger than the ξ-component [$H_{0\xi} \sim H_0 \cos(\alpha) = H_0 \sin(\phi)$, $\alpha = 90° - \phi$] of the permanent magnetic field and ϕ is typically very small ($\phi \lesssim 5°$), switching current and power can be very low, which is an important consideration in microrelay design.

The operation principle can be summarized as follows. A permalloy cantilever in a uniform[1] magnetic field can have a clockwise or a counterclockwise torque depending on the angle between its long axis (easy axis, ξ) and the field. Two bistable states are possible when other forces can balance the torque. A coil can generate a momentary magnetic field to switch the orientation of magnetization along the beam and thus switch the cantilever between the two states. Next, we discuss the design and fabrication.

III. Design and Fabrication

A. Torque and Force Calculations

Assuming a uniform magnetization of the beam, the magnetic moment can be expressed as $\boldsymbol{m} = M V$, where M is the magnetization in the beam and is determined by the external magnetic field, the beam geometry and magnetic properties, and V is the volume of the beam. The magnetic bending moment τ_m is obtained using

$$\tau_m = \boldsymbol{m} \times \boldsymbol{B}_0 = \mu_0 \boldsymbol{m} \times \boldsymbol{H}_0 \tag{1}$$

where $\boldsymbol{B}_0 = \mu_0 \boldsymbol{H}_0$ is the magnetic induction of the applied field and μ_0 is the permeability of free space.

Unlike other cantilever switches, these relays do not rely on a mechanical restoring force to operate. In fact, the elastic mechanical forces associated with the cantilever are generally parasitic contributions (except to define the open-switch deflection endpoint) and, as discussed below, are intentionally reduced by

[1]In practice, the field can be just approximately uniform.

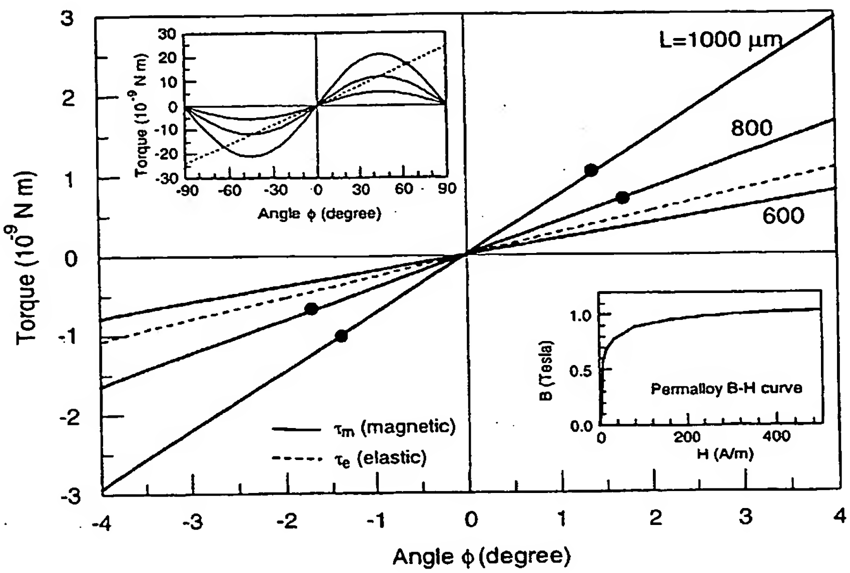

Fig. 4. Calculated magnetic and elastic (in the flexure) torque of the cantilever with three different lengths according to (1) and (3) respectively. In this particular case, two stable states (filled circles) exist for the two longer cantilevers (800 and 1000 μm) while only one stable state is possible for the short beam (600 μm). The elastic torque (dashed) exceeds the magnetic torque (solid) for all ϕ for the short beam. The top-left inset is an exploded plot showing the whole deflection range. The bottom-right inset shows the permalloy B–H curve used for the cantilever in our calculation. Other parameters are: $H_0 = 370$ Oersted, the cantilever dimensions are: $w = 200$ μm, $t = 25$ μm, $r = 2$ μm, $h = 12$ μm. The flexure dimensions are 280 μm × 20 μm × 3 μm.

design. If we neglect the elastic force, the contact force magnitude is

$$F \approx \frac{\tau_m}{L_r} = rwt\mu_0 M H_0 \sin(\alpha) \quad (2)$$

where L_r is the length of the beam to the right of the pivot (on the contact end), and $r = L/L_r$. When L_r approaches L, the cantilever transitions from hinged-type to the one-end-fixed type. All parameters (r, w, t, H_0, α) appearing explicitly in (2) affect the force and thus the contact resistance. Other parameters, such as the susceptibility χ and the demagnetization factors (D_i, $i = x, y, z$) can also implicitly affect the force through the M–H dependence.

At this point, it is appropriate to consider two important issues: bistability and contact resistance. From the above discussions, we know that the magnetic bending moment is bi-directional depending on the angle between $\boldsymbol{m}$ and $\boldsymbol{H}_0$. Bistability exists as long as other factors (such as the elastic torque due to the cantilever) are not dominant. Consider the structure shown in Figs. 1 and 2(a) where a cantilever is supported by torsion flexures from the two sides each having a length L_s, thickness t_s, width w_s, positioned at L_r from the right-end. The magnitude of the elastic torque τ_e is given by [22]

$$\tau_e = \frac{G\kappa t_s {w_s}^3}{L_s}\beta \quad (3)$$

where β is the string twist angle around its section-center and G is the shear modulus of the string material. For gold, $G = 27$ GPa is used in the calculation. κ is a constant determined by the ratio of t_s/w_s. In reality, the flexures may not be confined to only rotate around their center, it can also be stretched vertically or horizontally when the cantilever rotates. Consequently,(3) is an approximation. We have also neglected the gravitational effect because it is insignificant compared to the magnetic effects in this case. Fig. 4 shows the calculated magnetic and elastic torque according to (1) and (3), respectively. The magnetic field strength used in the calculation is $H_0 = 370$ Oersted (2.94×10^4 A/m), which corresponds to $B_0 = 0.037$ Tesla and the torsion flexure is placed at the center of the cantilever ($r = 2$) in the calculation (other parameters are given in the figure caption). It can be seen that the magnetic torque is larger than the elastic torque ($|\tau_m| > |\tau_e|$) for small angle ϕ in the cantilevers with lengths of 800 and 1000 μm while the elastic torque dominates in the shorter cantilever ($L = 600$ μm). Thus, bistability exists in the two longer cantilevers but not in the short one. For an air gap spacing of $h = 12$ μm, the two stable positions are $\phi = \pm\sin^{-1}(12/500) = \pm 1.38°$ for the cantilever of length 1000 μm and $\phi = \pm\sin^{-1}(12/400) = \pm 1.72°$ for the cantilever of length 800 μm, if we neglect the bottom contact height. A larger angle yields a more stable relay because of the larger magnetic torque preventing the cantilever from switching. The tradeoff is the requirement of a larger switching current and thus higher power consumption.

The contact force critically determines the contact resistance. From (2) we can see that all the geometry factors (r, w, t) affect the force. In our design, the permanent magnetic field holds the cantilever to the "on" or "off" state without any power consumption. Thus the magnetization (M) in the cantilever is induced purely by the permanent magnet during the quiescent mode and is directed along the easy axis (ξ in Fig. 3) due to the geometry. This M is proportional to the ξ component of H_0: $M \sim \chi H_0 \cos(\alpha)$. For a strictly uniform magnetic field H_0 in the vertical direction and when the cantilever is in the horizontal position ($\alpha = 90°$), M is essentially zero, an unstable equilibrium state. Larger angle ϕ gives a larger M, and a larger

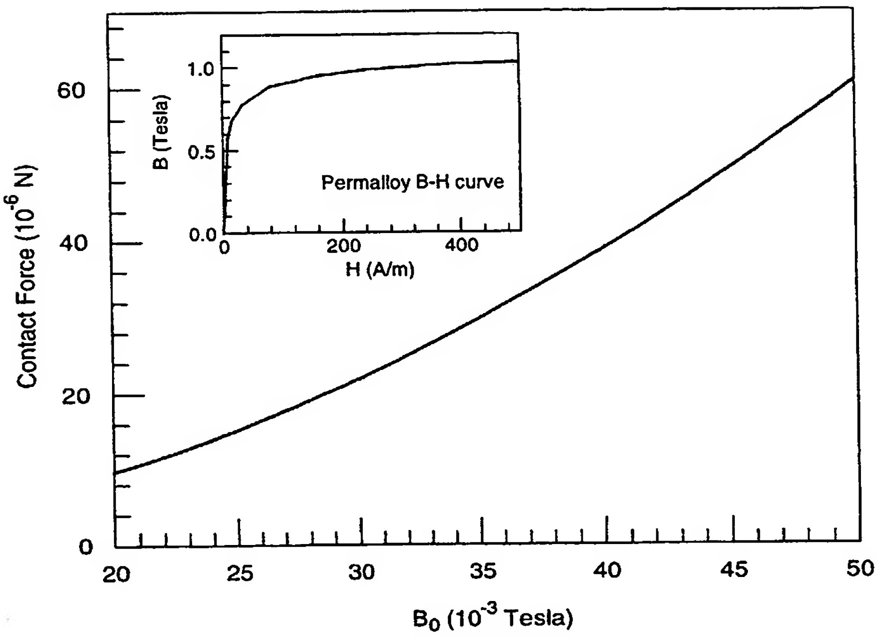

Fig. 5. Calculated contact force as a function of the permanent magnetic flux B_0 [see (2)]. The cantilever dimensions are the same as in Fig. 4.

force. For a given air gap spacing, the angle ϕ can be adjusted by choosing the location of the supporting torsion flexure (or $r = L/L_r$). Contact forces are calculated using (2) and shown as functions of external magnetic field strength in Fig. 5. We can see that the contact force increases with B_0 with a larger than linear slope.

B. Switching Field

The current-induced coil magnetic field has both an X and a Z component. It is mainly the X component that is used for switching.

The magnetic field distribution around the planar coil can be calculated using the Biot-Savart Law as follows:

$$B_{\text{coil}} = \frac{\mu_0}{4\pi} \int \frac{I dl \times r}{r^3}. \tag{4}$$

A numerical analysis was used to calculate the magnetic field distribution. The calculated magnetic induction at positions $Z = 4$ μm above the X-axis is shown in Fig. 6. $B_{\text{coil-}Z}$ and $B_{\text{coil-}X}$ are the components along Z- and X-axis respectively. The coil has 25 turns with an equal spacing of $\Delta X = 20$ μm between the turns. The current in the coil is 50 mA. Because the beam lies in the positive side of the X-axis, the X-component of the magnetic field is shown in greater detail for this region in Fig. 6(b) (for several different heights, Z = 4–32 μm). The oscillatory behavior in B_{coil} for small ($Z = 4$ μm) is due to the finite spacing ($\Delta X = 20$ μm) between coil lines and gradually disappears when Z becomes large. The average induction strength is in the range between 0.001 Tesla and 0.002 Tesla.

To evaluate under what conditions the coil current can switch the relay, the magnetization process needs to be examined in more detail. As mentioned above, when the aspect ratio of a beam is large (i.e., $L > w \gg t$), the magnetization primarily aligns in the direction of L. Much smaller components of the magnetization also exist along the directions of w and t, but can be neglected due to the large demagnetization in these directions. Thus the beam's magnetization is primarily determined by the external field component along its long axis. To switch

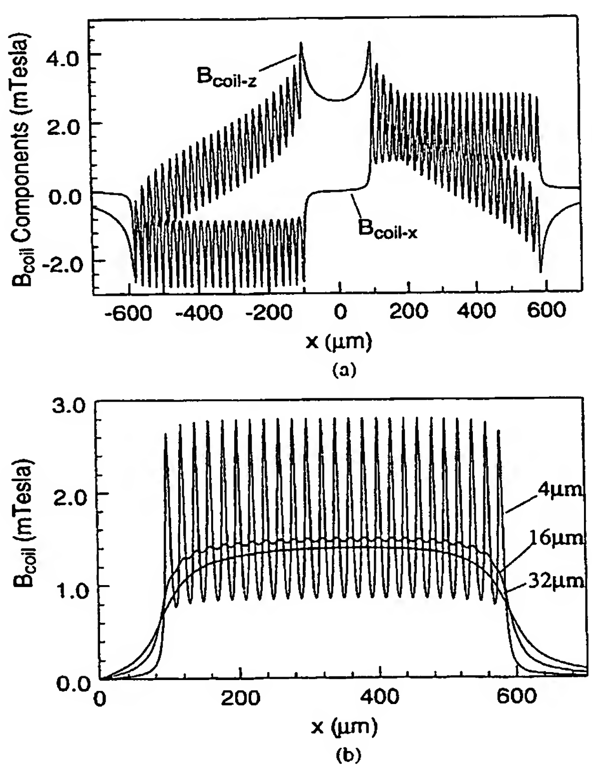

Fig. 6. (a) Calculated coil current-induced magnetic field (X- and Z-components) at 4 μm above the coil. (b) The X-component of the coil current-induced magnetic field at 4, 16, and 32 μm above the coil. The origin of the axis is located at the center of the planar coil.

the relay, the coil current-induced magnetic field ($B_{coil\text{-}\xi}$) must overcome the external field ($B_{0\xi}$) along the cantilever's length, at least momentarily.

Consider the center-hinged type cantilever as an example to estimate the magnetic field strengths. We assume $L = 800\ \mu m$, $w = 200\ \mu m$, $t = 25\ \mu m$, the stage height (air gap spacing) $h = 12\ \mu m$, and the external magnetic field $B_0 = 0.037$ Tesla (equivalent to $H_0 = B_0/\mu_0 = [0.037/(4\pi \times 10^{-7})] \times 4\pi \times 10^{-3} = 370$ Oersted). The key purpose is to verify that $B_{coil\text{-}\xi} > B_{0\xi}$ when the cantilever is in the "close" position (the result also applies to the "open" case because of the symmetry). $B_{0\xi}$ depends on both B_0 and the angle α [$B_{0\xi} = B_0 \cos(\alpha)$]. When the cantilever is in the "close" position, we obtain $\alpha = 180°\text{- arccos } (12/0.5L) = 180°\text{- arccos } (12/400) = 91.72°$. So, we have $B_{0\xi} = -0.0011$ Tesla. On the other hand, $B_{coil\text{-}\xi} \approx B_{coil\text{-}X} \sin(\alpha) \approx B_{coil\text{-}X}$, and its average value is around 0.0014 Tesla at the height of 12 μm [see Fig. 5(b)]. We can see that under these conditions, a 50 mA current in the planar coil is able to generate a magnetic field large enough to reverse the magnetization in the cantilever and switch the relay. The analysis applies to other cases where the supporting torsion flexure is not located exactly at the center of the cantilever ($r = 2$), and the switching current can be different between the two switching events. Another point worth noting is that because current-induced coil magnetic field only needs to overcome the ξ-component of the external field (B_0) and not the ω component, the switching current can be relatively small.

C. Fabrication

Conventional surface micromachining techniques were used to fabricate the latching relays. The device was fabricated on a Si-substrate covered with an insulating dielectric. An Ag coil was formed by e-beam evaporation and wet etching. A polyimide layer was spin-cast on to cover the coils. Then bottom Au contact layers were deposited and patterned. Photoresist was used as a sacrificial layer. The cantilever was formed by electroplating NiFe permalloy on a Au seed layer. The cantilever was then released, and the relay diced and finally mounted on a permanent magnet.

IV. Results and Discussion

Latching micro relays of both the center-hinge and fixed-end type have successfully been demonstrated. A number of different beam dimensions—ranging from $10\ \mu m \le w \le 600\ \mu m$, $80\ \mu m \le L \le 1000\ \mu m$, $10\ \mu m \le t \le 30\ \mu m$, and $12\ \mu m \le h \le 18\ \mu m$—have been evaluated for both cantilever types. A 20-turn coil was used for all the devices.

Photographs of two types of micro magnetic relays (center-hinged and fixed-end) are shown in Fig. 2. Both types are fully functional; demonstrating both latching operation and electrical switching.

A. Resistance

Resistance was measured using the four-probe method. For a typical hinged-type relay ($L = 1000\ \mu m$, $w = 500\ \mu m$, $t = 30\ \mu m$, $h = 18\ \mu m$, $L_s = 280\ \mu m$, $w_s = 40\ \mu m$, $t_s = 4\ \mu m$, $L_r = 190\ \mu m$ or $r = 2.63$), the measured lead-to-lead resistance was 52.8 mΩ under a 410 Oersted permanent magnet field with a switching current of 118 mA. It is interesting to note that, for this particular device, the series resistance increased to 71 mΩ when the magnetic field was reduced to 315 Oersted, but the switching current could then be reduced to less than 100 mA. We have estimated the series resistance due to the torsion flexures to be around 20 mΩ.

The corresponding contact forces were estimated using (2) (see also Fig. 5). For the relay with parameters provided in the previous paragraph, the calculated contact forces were around 24 μN and 41 μN for the magnetic field strengths of 315 Oersted and 410 Oersted, respectively. These values are consistent with the resistance range of 10–70 mΩ derived from Schimkat's work [23], and does not differ greatly from the 80 to 200 mΩ range obtained from Hyman and Mehregancy's work [24]. In our calculation, we have neglected the restoring force due to the torsion flexures and the net attractive magnetic force due to the nonuniform field distribution. The torsion flexure decreases the contact force and the attractive magnetic force increases it.

B. Switching Characteristics

Electrical switching characteristics are shown in Fig. 7. A waveform generator (HP33120A) was used to produce the coil current pulses for switching. A dc voltage of 3.2 V was applied to the relay with a load resistor ($R_L = 5$ kΩ) in series. Both the input signal (V_{in}) and the relay signal (V_R on the load) were recorded on an HP Oscilloscope (HP54615B). The input pulse width was 0.2 ms and the duty cycle was 10 ms. The magnitude of the driving pulse was 5.9 V, which corresponds to a current of 79 mA with a coil resistance of 75 Ω. As can be seen, a negative current pulse through the coil turns off the relay and a positive pulse turns on the relay. Between the pulses, the relay latches in a stable state without any power consumption. The turn-on and -off transient characteristics are shown in the enlarged plots in Fig. 7. The input current pulse rise time is approximately 0.01 ms. The relay has a much faster response from the "on" to "off" state than from the "off" to "on" state. The transient results show that the relay is switched off within 0.07 ms and is switched on within 0.40 ms after the switching pulse is triggered. It is not too difficult to understand this difference in the relay response time, which is explained as follows.

The total relay switching time is determined by the sum of the following factors:

1) the rise time of the coil current to its critical switching value;
2) the time to realign the magnetization of the cantilever;
3) the contact adhesion;
4) the traveling time for the cantilever to rotate from one state to the other.

The bottleneck is 4), at least for the "off" to "on" switching. In order for the relay to be switched on, the cantilever needs to close the gap, which is ~ 12 μm. How fast the cantilever can rotate depends on the magnitude of the torque and the cantilever's moment of inertia. In general, a faster time can be obtained with a larger torque, smaller moment of inertia, and smaller gap.

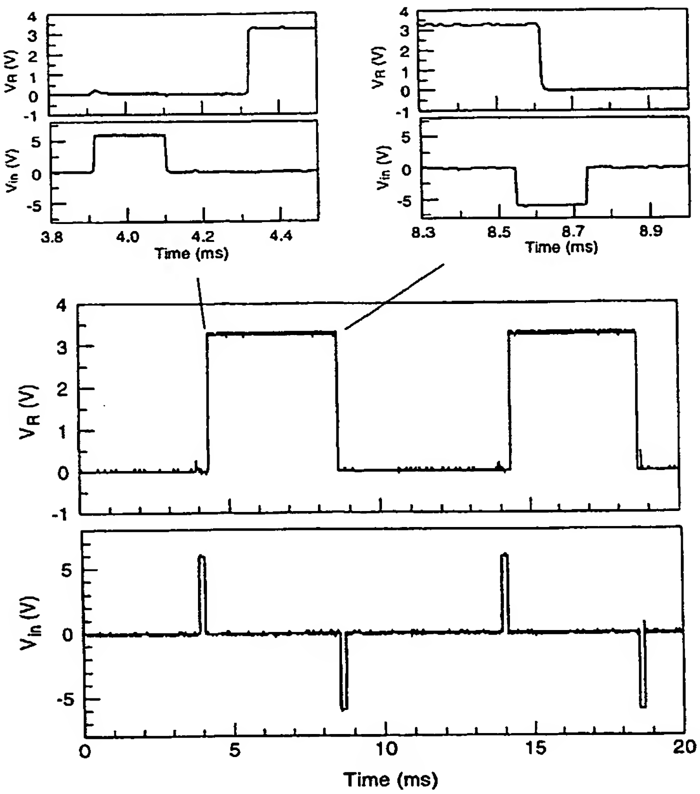

Fig. 7. Measured switching characteristics of the relay. The driving voltage pulse (V_{in}) magnitude is ±5.9 V with a pulse width of 0.2 ms. The corresponding driving current pulse magnitude is ±79 mA. The relay dimensions are 800 μm × 200 μm × 25 μm with the torsion flexure located at the cantilever center ($r = 2$). The dimensions of each flexure are 280 μm × 20 μm × 3 μm. The air gap pacing is 12 μm. The permanent magnet field strength is 370 Oersted (0.037 Tesla).

We have estimated the switching time based on the relay parameters given above. The magnetic bending moment ($|\tau_m| = 8.7 \times 10^{-10}$ N-m) is calculated using (1) by using the cantilever magnetic moment ($|m| = 2.35 \times 10^{-8}$ A-m^2) due to the coil-current-induced field ($B_{\text{coil-}\xi} = 0.0012$ Tesla). We have used $H_0 = 370$ Oersted (2.94×10^4 A/m) in the calculation. For simplicity, we assume $|\tau_m|$ to be a constant during switching. The approximation is not too bad considering the small rotation angle $\Delta\alpha$ from "off" to "on" state ($88.3° \leq \alpha \leq 91.7°$ in this design, so $\Delta\alpha = 3.4°$). The moment of inertia of the cantilever around its center is

$$I = \frac{1}{12}\mu \cdot L^2 \tag{5}$$

where μ is the cantilever's mass. I is estimated to be about 1.9×10^{-15} kg · m^2. So from equation

$$\tau_m = I\frac{d^2\alpha}{dt^2} \tag{6}$$

we can derive the time for the cantilever to travel from "off" to "on" to be

$$t_{\text{off}\rightarrow\text{on}} = \sqrt{\frac{2I \cdot \Delta\alpha}{\tau_m}}. \tag{7}$$

The calculated traveling time is about 0.51 ms, in close agreement with the observed result.

The time to switch off the relay is much shorter because as soon as the cantilever leaves the bottom contact, the electrical connection is open. Ideally, this delay should be approximately equal to the time for the switching current to rise to a critical switching value plus the time to reverse the magnetization, which is a fast process. The origin of the much longer measured delay time 0.07 ms ($\gg$ 0.01 ms) delay is not fully understood. It may be due to contact adhesion (van der Waals force, electrostatic forces, or bridging at the contact due to heating, etc.), which hinders the cantilever's release from the bottom contact.

The minimum switching pulse width determines the minimum switching energy consumption. For the device under discussion, the measured minimum switching pulse width is 0.2 ms with a switching current magnitude of 79 mA (5.9 V) and a permanent field strength of $H_0 = 370$ Oersted (2.94×10^4 A/m). The minimum switching energy is thus 93 μJ. For latching purposes, the minimum switching pulse width is determined by the time for the cantilever to travel from its stable position (either "up" or "down") to the horizontal position ($\alpha = 90°$). Too short a switching pulse will result in the cantilever reversing its direction of rotation and returning to its original state without switching. For this reason, we can expect the minimum switching pulse width to be equal to $t_{\text{off}\rightarrow\text{on}}/2 \approx 0.25$ ms (compared to the measured value of 0.2 ms), and to be approximately equal for "off" to "on" and "on" to "off" cases (symmetrical design with $r = 2$), which is consistent with observations.

C. Reliability

The maximum dc current is > 500 mA. Lifetime tests were performed on a relay with the following dimensions: $L = 1000$ μm, $w = 500$ μm, $t = 30$ μm, $L_s = 280$ μm, $w_s = 40$ μm, $t_s = 4$ μm, $r = 2$, $h = 12$ μm. The permanent magnetic field strength was 370 Oersted and the switching current was 100 mA. No mechanical or electrical degradation (permanent contact resistance change) were observed after the relay was switched for 4.8×10^6 cycles in ambient conditions with an "on" current of 240 μA. Momentary resistance changes were occasionally observed during test and might have been due to particles in the air. Further evaluations are under way to better understand the long-term contact properties.

V. Summary

This paper describes a new type of latching micro magnetic relay (see Fig. 1) that has recently been demonstrated. The device is based on preferential magnetization of a permalloy cantilever in a permanent external magnetic field. Switching between two stable states is accomplished by a short current pulse through an integrated coil underneath the cantilever. Some key features are summarized as follows:

1) latching (bistable);
2) low energy consumption during switching (< 93 μJ, switching current ~ 79 mA, minimum switching pulse width ~ 0.2 ms);
3) low voltage operation (< 5 V);

4) maximum dc current > 500 mA;
5) capable of various switch configurations [single-pole-single-throw (SPST), multi-pole-single-throw (MPST), or multi-pole-double-throw (MPDT)];
6) low contact resistance (< 50 mΩ);
7) operation in ambient environment;
8) lifetime expected to be comparable to other micro relays;
9) batch fabrication using planar processing methods.

The most significant advantage of this relay is its bistability and consequent elimination of power consumption in the quiescent states. Other desirable properties (such as low contact resistance, low operation voltage, high off-state isolation, simplicity of design and fabrication, fast switching and large actuation force) also make the device a good candidate for applications in automatic testing equipment, smart interconnects, and other fields that require latching relays.

ACKNOWLEDGMENT

The authors also acknowledge valuable technical contributions from Dr. W. Wilson of the Air Force Research Laboratory (AFRL).

REFERENCES

[1] S. Majumder, N. E. McGruer, and P. M. Zavracky, "Electrostatically actuated micromechanical switches," *J. Vac. Sci. Technol. A*, vol. 15, no. 3, pp. 1246–1249, 1997.
[2] S. Majumder, N. E. McGruer, P. M. Zavracky, G. Adams, R. Morrison, and J. Krim, "Measurement and modeling of surface micromachined, electrostatically actuated microswitches," in *Proc. 1997 Int. Conf. Solid-State Sensors and Actuators (Transducers '97)*, 1997, pp. 1145–1148.
[3] N. S. Barker and G. M. Rebeiz, "Distributed MEMS true-time delay phase shifters and wide-band switches," *IEEE Trans. Microwave Theory Tech.*, vol. 46, no. 11, pp. 1881–1889, 1998.
[4] P. M. Zavracky, S. Majumder, and N. E. McGruer, "Micromechanical switches fabricated using nickel surface micromachining," *J. Microelectromech. Syst.*, vol. 6, pp. 3–8, Mar. 1997.
[5] C. Goldsmith, J. Randall, S. Eshelman, T. H. Lin, D. Denniston, S. Chen, and B. Norvell, "Characteristics of micromachined switches at microwave frequencies," *IEEE MTT-S Dig.*, pp. 1141–1144, 1996.
[6] C. Goldsmith, T.-H. Lin, B. Powers, W.-R. Wu, and B. Norvell, "Micromechanical membrane switches for microwave applications," *IEEE MTT-S Dig.*, pp. 91–94, 1995.
[7] R. Mattiuzzo. (1999) Siemens Electromechanical Components. [Online]. Available: http://www.siemens.de
[8] W. P. Taylor, O. Brand, and M. G. Allen, "Fully integrated magnetically actuated micromachined relays," *J. Microelectromech. Syst.*, vol. 7, pp. 181–191, 1998.
[9] W. P. Taylor and M. G. Allen, "Integrated magnetic microrelays: normally open, normally closed, and multi-pole devices," in *Proc. 1997 Int. Conf. Solid-State Sensors and Actuators (Transducers '97)*, 1997, pp. 1149–1152.
[10] J. A. Wright, Y.-C. Tai, and G. Lilienthal, "A magnetostatic MEMS switch for DC brushless motor commutation," in *Proc. Solid-State Sensor and Actuator Workshop 1998*, Hilton Head Island, SC, 1998, pp. 304–307.
[11] J. A. Wright and Y.-C. Tai, "Micro-miniature electromagnetic switches fabricated using MEMS technology," in *Proc. 46th Annu. Int. Relay Conf.: NARM'98*, Oak Brook, IL, April 1998, pp. 13-1–13-4.
[12] J. Wright, Y.-C. Tai, and S.-C. Chang, "A large-force, fully integrated MEMS magnetic actuator," in *Proc. 1997 Int. Conf. Solid-State Sensors and Actuators (Transducers '97)*, vol. 2, 1997, pp. 793–796.
[13] H. A. C. Tilmans, E. Fullin, H. Ziad, M. D. J. Van de Peer, J. Kesters, E. Van Geffen, J. Bergqvist, M. Pantus, E. Beyne, K. Baert, and F. Naso, "A fully-packaged electromagnetic microrelay," in *Proc. IEEE 12th Annual Int. Conf. MEMS*, 1999, pp. 25–30.
[14] E. Fullin, J. Gobet, H. A. C. Tilmans, and J. Bergqvist, "A new basic technology for magnetic micro-actuators," in *Proc. IEEE Microelectromechanical Systems*, Heidelberg, Germany, 1998, pp. 143–147.
[15] J. W. Judy and R. S. Muller, "Batch-fabricated, addressable, magnetically actuated microstructures," in *Proc. Solid-State Sensor and Actuator Workshop*, Hilton Head, SC, 1996, pp. 187–190.
[16] ——, "Magnetically actuated, addressable microstructures," *J. Microelectromech. Syst.*, vol. 6, p. 249, 1997.
[17] C. H. Ahn and M. G. Allen, "A fully integrated micromagnetic actuator with a multilevel meander magnetic core," in *Proc. Solid-State Sensor and Actuator Workshop*, Hilton Head, SC, 1992, pp. 14–18.
[18] L. K. Lagorce, O. Brand, and M. G. Allen, "Magnetic microactuators based on polymer magnets," *J. Microelectromech. Syst.*, vol. 8, pp. 2–9, Mar. 1999.
[19] X.-Q. Sun, K. R. Farmer, and W. N. Carr, "A bistable microrelay based on two-segment multimorph cantilever actuators," in *Proc. IEEE Microelectromech. Syst.*, Heidelberg, Germany, 1998, pp. 154–159.
[20] E. J. J. Kruglick and K. S. J. Pister, "Bistable MEMS relays and contact characterization," in Solid-State Sensor and Actuator Workshop (Hilton Head '98).
[21] J. H. Comtois and V. M. Bright, "Surface micromachined poly-silicon thermal actuator arrays and applications," in *Proc. Solid-State Sensor and Actuator Workshop*, Hilton Head, SC, 1996, pp. 174–177.
[22] G. W. van Santen, *Introduction to a Study of Mechanical Vibration*. London, U.K.: Cleaver-Hume Press, 1961, p. 26.
[23] J. Schimkat, "Contact materials for microrelays," in *Proc. IEEE Microelectromech. Syst.*, Heidelberg, Germany, 1998, pp. 190–194.
[24] D. Hyman and M. Mehregany, "Contact physics of gold microcontacts for MEMS switches," in *Proc. 44th IEEE Holm Conf. Electr. Contacts*, 1998, p. 133.

Meichun Ruan received the B.S. degree in physics from University of Science & Technology of China in 1991, the M.S. degree from Shanghai Institute of Nuclear Research in 1994, and the Ph.D. degree in electrical engineering from Arizona State University, Tempe, in 2000.

He is currently with Microlab, Inc., Chandler, AZ. His interest is in the development of magnetic MEMS devices.

Jun Shen (M'90–SM'98) received the B.S. degree in South China University of Science and Technology, the M.S. degree from Texas Tech University, Lubbock, and the Ph.D. degree from the University of Notre Dame, IN, all in physics in 1982, 1984, and 1990, respectively.

He was with Motorola, Inc., for six years before joining the faculty of the Department of Electrical Engineering, Arizona State University, Tempe, in 1996. His research interests include semiconductor physics and micromachined devices. He is inventor/coinventor of 25 issued U.S. patents and published many technical articles.

Dr. Shen received the Motorola Distinguished Innovator Award in 1994.

Charles B. Wheeler (S'87–M'98) received the Ph.D. degree in electrical engineering from Arizona State University, Tempe, in 1998 and the B.S. degree in materials science from Stanford University, Stanford, CA, in 1985.

He has worked in semiconductor manufacturing with GTE Microcircuits and AGI Consulting and has worked in the field of photonics research at Intelligent Automations, Inc. In 1998, he cofounded Microlab, Inc., Chandler, AZ, and since that time has been involved with the development and commercialization of magnetic latching MEMS devices.